CHAPTER 3
Design of Landfill Off-Gas Collection Systems

3.1. **General**. Gas control systems consist of collection, conveyance, and treatment components and are designed to be either passive or active. A passive system allows the landfill gas to exit the collection system without mechanical assistance, whereas an active system uses mechanical assistance, such as blowers, to extract gases. Depending on the potential impacts of the landfill gas and local regulatory criteria, gases are either dispersed into the atmosphere or collected and treated. Design of collection systems and conveyance piping are described in this section.

3.2. **Methods of Gas Collection**. LFG is generally collected using gas collection wells, blankets, or trenches. The following sections describe each of these types of systems.

3.2.1. *Wells.* Well systems consist of a series of vertical gas extraction wells (perforated or slotted collection pipes) that penetrate to near the bottom of the refuse or to near the depth of saturated waste. Well systems are often recommended for landfills or portions of landfills that exceed 12 m (40 ft) in depth. The design of a well system requires an estimate of the rate of gas production and the radius of influence of the wells. A well system, either active or passive, is useful for layered landfills where vertical gas migration is impeded. Because of the variability of landfill refuse, design procedures are difficult to apply to gas collection systems. Gas collection wells are commonly spaced at a frequency of one per acre and are constructed using an auger type drill rig.

3.2.1.1. *Active Gas Vent Well Design.* The method of construction and components of active LFG extraction wells are similar to those of standard ground water monitoring or extraction wells (i.e., riser, screen, gravel pack).

3.2.1.1.1. *Borehole.* The borehole diameter for an active gas collection well will typically range from 0.3 to 1 m (1 to 3 ft). The well boring will typically extend from the landfill surface to near the bottom of the waste. If the landfill contains a liner system beneath the waste, the well should be terminated a safe distance above the liner system to prevent damage.

3.2.1.1.2. *Casing.* A minimum 100 mm (4-inch) diameter HDPE or PVC casing is placed in the boring. The casing diameter should be based on pneumatic analysis of the system and anticipated LFG flow rates. In cases where landfill temperatures are high, other screen/casing materials such as steel and fiberglass should be considered. The operating service temperature range for HDPE pipe is reported to be -45.6 to 60^0 C (-50 to 140°F) for pressure service, and up to 82.2^0 C (180°F) for nonpressure service. The maximum operating service temperature for PVC is reported to be 60^0 C (140°F). The casing should be placed in the center of the borehole.

3.2.1.1.3. *Centralizers.* Centralizers center the casing in the borehole and must be a size appropriate for the casing and borehole. These are recommended for holes greater than 6 m (18 ft) deep. Select centralizers made of material that will not lead to galvanic corrosion of the casing. Stainless steel centralizers are recommended with PVC or stainless steel casing.

3.2.1.1.4. *Screen.* The bottom two-thirds of the well should be screened using either a perforated or slotted casing. However, if the cover system does not contain a geomembrane, the casing should extend a minimum of 3.048 to 4.572 meters (10 to 15 feet) into the waste. Perforated pipe with 15 mm (0.5 inch) diameter holes spaced at 90 degrees every 0.15 to 0.3 m (6 to 12 inches) may be used. Slotted or continuous wrap screen may also be used. Continuous-wrap screen is preferred because the increased open area reduces the pressure drop across the screen and, therefore, reduces energy costs for the blower. Slot size should generally be a minimum of 2.5 mm (0.10 in.) but should be as large as possible to reduce the vacuum drop across the screen. End caps consistent with the screen type should be specified for the bottom of the well screen.

3.2.1.1.5. *Gravel Pack.* A gravel pack should be placed around the screen. The gravel pack should extend a minimum of .3 m (12 in.) above the end of the screen. The gradation of the gravel pack will be dependent on the gradation of the waste surrounding the well and the diameter of the borehole. Typically, washed river gravel or crushed stone is used. AASHTO No. 57 stone has been specified on several USACE projects.

3.2.1.1.6. *Seal and Grout.* A 1.3 m (4 foot) layer of bentonite material is placed on top of the gravel. A 0.3 m (12 inch) layer of fine sand should be placed between the gravel pack and grout if bentonite grout is used. The remainder of the borehole can be backfilled with cement-bentonite grout or a granular soil. Figure 3.1 is an example of an active gas extraction well. A 0.3 m (12 inch) thick bentonite seal is sometimes placed on top of the granular soil layer just beneath the cover system.

3.2.1.1.7. *Slip Couplings.* Slip couplings are often used if settlement is likely to be severe. The slip coupling allows the well to telescope down as settlement occurs. A prefabricated boot should be used to attach any geomembranes in the landfill cover to the gas vent pipe. This will help minimize leakage of atmospheric air into the landfill.

3.2.1.2. *Passive Gas Vent Well Design.* A passive gas vent well should be similar in design to an active extraction well. The well should be constructed of PVC or HDPE and should be a minimum of 100 mm (4 inches) in diameter. The pipe should be placed in the center of a 300 - 600 mm (1 to 2 foot) diameter borehole and backfilled with gravel to a level of 3 foot (.3 to 1 m) above the perforated or slotted section. The remainder of the hole should be backfilled in a fashion similar to an active gas vent well. Figure 3.2 is an example of a passive gas vent well.

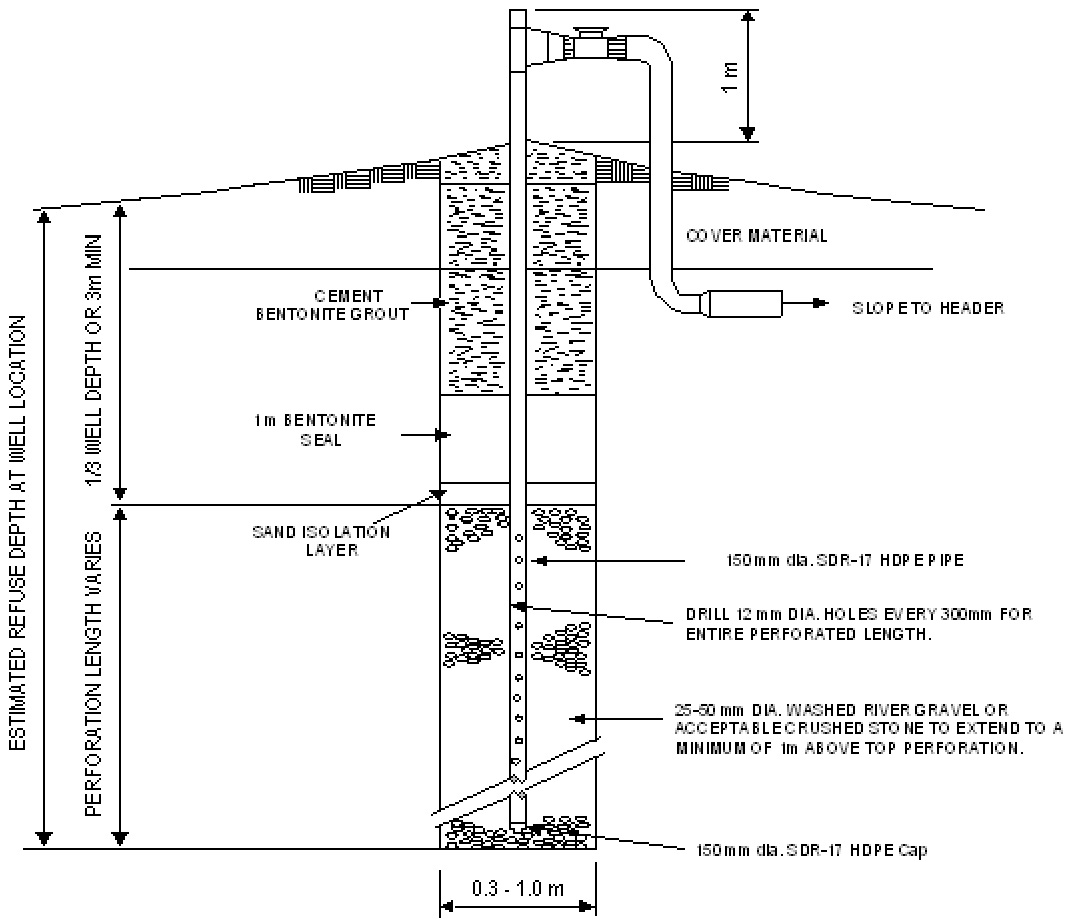

Figure 3.1. Typical Landfill Gas Extraction Well.

3.2.2. *Blanket Collection Systems.* The EPA recommends that continuous blanket collection systems constructed of sand or gravel be a minimum of 0.3 m (12 inches) in thickness and located below the impermeable barrier layer. A geosynthetic blanket with equivalent transmissivity properties can also be used. A continuous blanket system will allow free movement of gases to either collection or outlet pipes. Vertical outlet pipes transport the collected gases from beneath the landfill cover. The number of vent pipes should be minimized and are normally spaced about 60 m (200 ft) apart. This provides approximately one vent per acre. Perforated horizontal collection pipes can also be incorporated into the design of either passive or active blanket systems. A geotextile filter layer may be required to prevent clogging of the gas collection blanket material. Continuous blanket systems are effective in preventing excessive pressure from building up beneath the low permeability layer. They are less effective in preventing off-site migration of gas since there are no wells extending into the refuse. Gas wells or perimeter trenches should generally be used if off-site migration of gas is a concern.

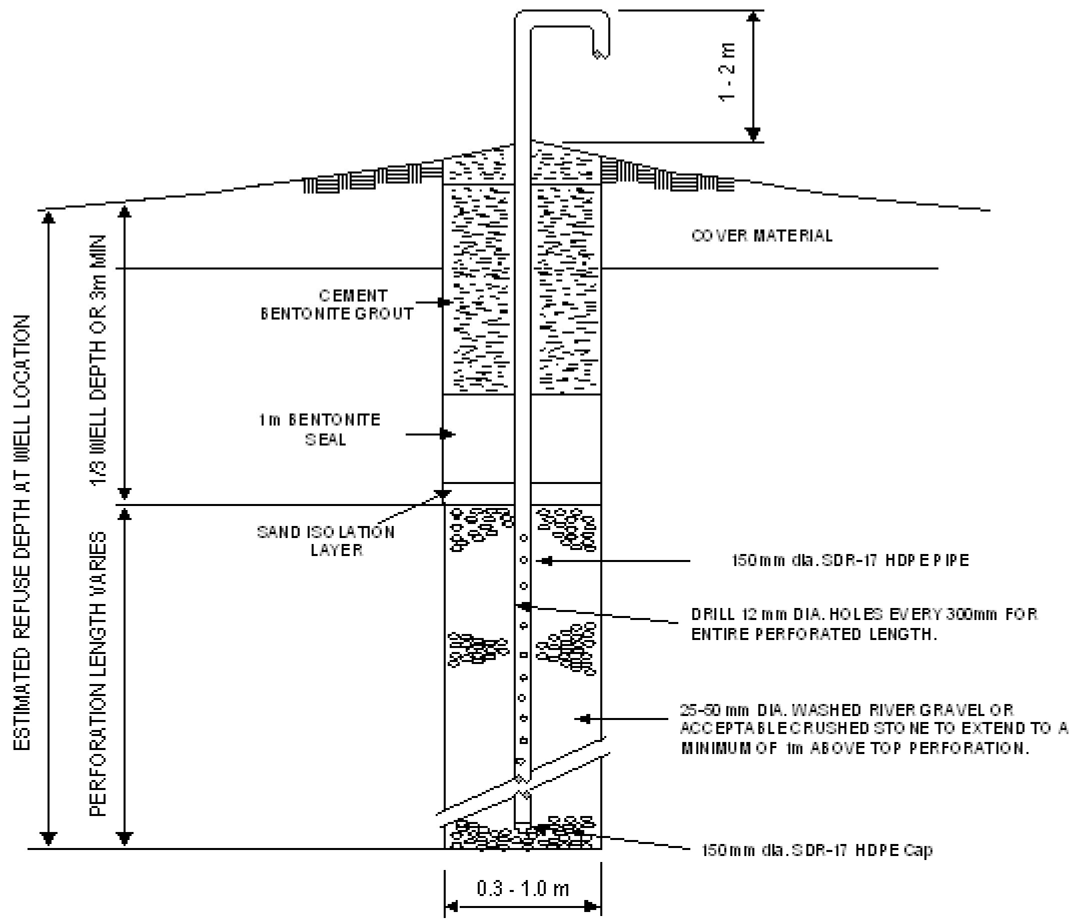

Figure 3.2. Passive Gas Vent Well.

3.2.2.1. *Granular Blankets.* The design of a granular collection blanket system requires choosing an appropriate material for use in the gas collection layer and determining the layer thickness. Typically, the minimum thickness is 0.3 m (12 inches). Granular material should have minimum fines to facilitate the flow of collected gas. AASHTO No. 57 stone is frequently specified for granular gas collection layers due to the general availability of this material. Geotextiles are often used to separate the granular blanket from other soils and refuse.

If large diameter (> 12.5 mm [0.5 in.]) or angular materials are used for the gas collection layer, overlying geomembranes should be protected with a geotextile or soil cushion layer. Geotextile cushion layers typically have a minimum weight of 0.4 kg/sq m (12 ounces/sq yard). Details regarding cushion layer design are given in Design Methodology for the Puncture Protection of Geomembranes (Wilson-Fahmy et al. 1996). Figure 3.3 shows a typical cross-section of a granular blanket gas vent layer.

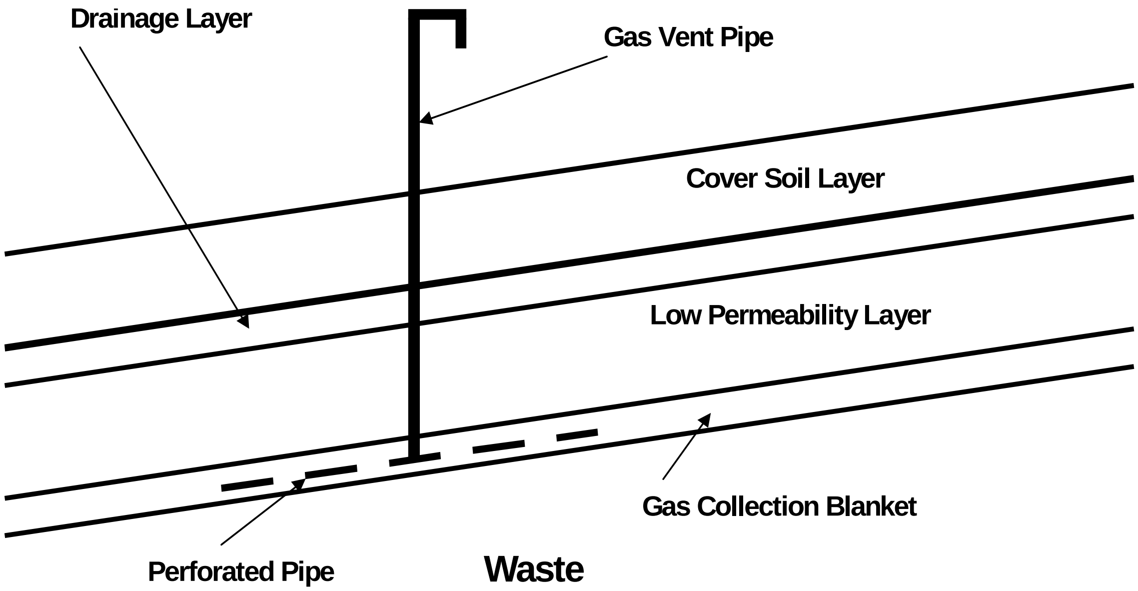

Figure 3.3. Gas Collection Blanket.

3.2.2.2. *Geosynthetic Blankets.* Geosynthetic gas collection systems have often been used to replace granular materials because they require less space and are easier to construct. A geosynthetic gas collection system typically consists of a three-dimensional geonet drainage core with a geotextile fabric attached to one or both sides. The geotextiles act as a filter/separator from adjacent layers of waste and soil. Geonets typically range from 5.0 to 8.0 mm (0.20 to 0.30 in.) in thickness but can be considerably thicker.

Thick nonwoven needlepunched (NWNP) geotextiles have also been used as gas collection blankets. However, they are effective only for very low volumes of gas and for low normal stresses. For these reasons, geonets/geocomposites are almost always preferred over geotextiles alone.

An example of a gas vent relief flap is shown in Figure 3.4. This flap design can be used with passive gas collection blanket systems where pipes that extend above the surface of the landfill are undesirable. The flap design configuration is only applicable where very low rates of gas generation are anticipated.

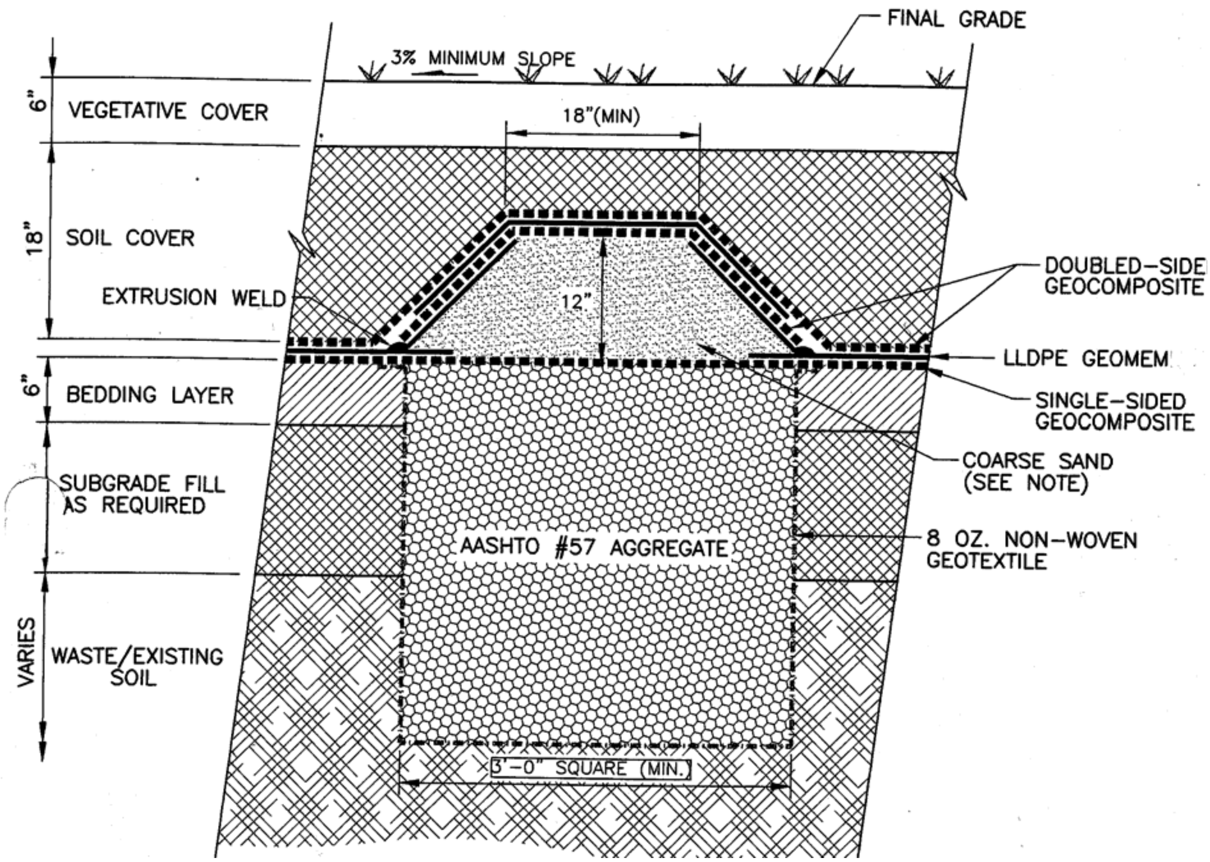

Figure 3.4. Gas Vent Relief Flap.

3.2.3. *Trenches.*

3.2.3.1. *Perimeter Trenches.* A trench can be constructed around the perimeter of a landfill to prevent the off-site migration of gas. The trench should extend from the ground surface to an impermeable geologic strata or the ground water table. The feasibility of installing a gas collection trench is dependent on the depth to the impermeable strata, the excavatability of the material into which the trench is being placed, and fluctuations in the ground water table. Collection trenches are typically 0.9 m or more (3ft or more) wide and are filled with gravel such as AASHTO No. 57 stone. Effectiveness can be improved by installing a 1.0 to 1.5 mm (40 to 60 mil) geomembrane on the outside wall of the trench. A protective geotextile should be placed between the collection rock and the geomembrane to prevent damage to the geomembrane. Seaming of geomembranes sheets within the trench is difficult and must be done using trench boxes to protect workers. A low permeability cover should be placed over the top of the collection trench to prevent precipitation from getting into the trench and saturating the collection rock. Figure 3.5 is an example of a perimeter gas collection trench.

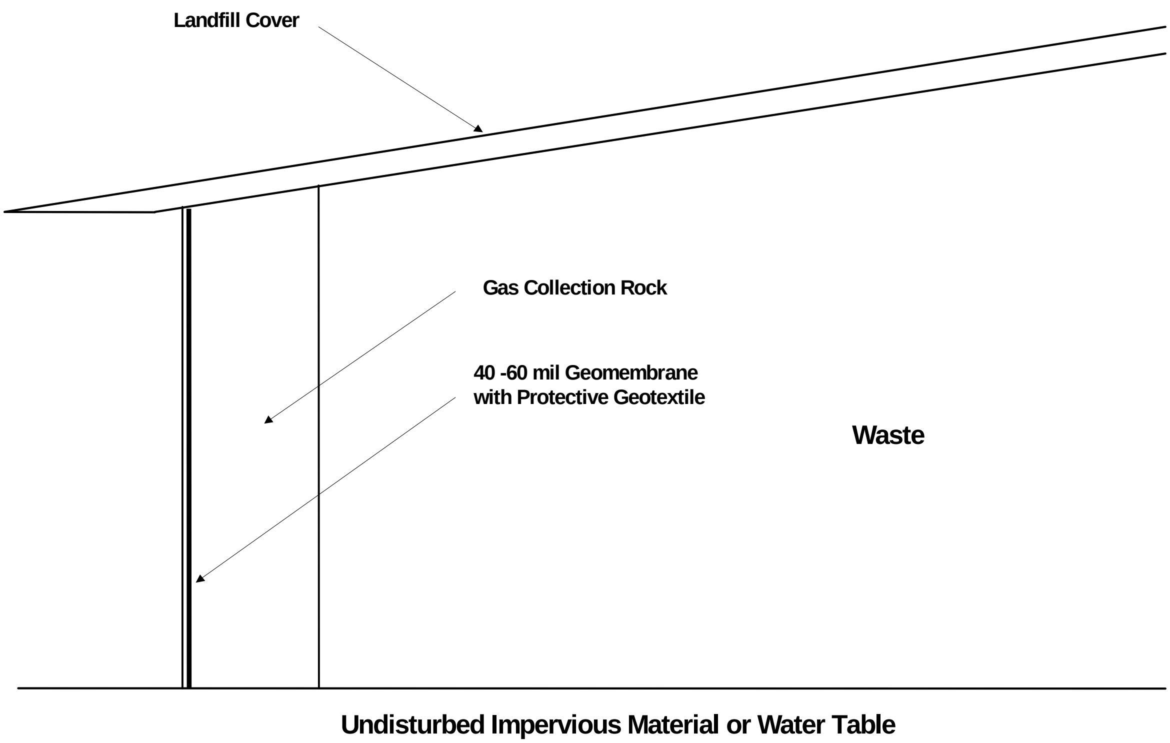

Figure 3.5. Perimeter Collection Trench.

3.2.3.2. *Surface Collection Trenches.* For landfills where the waste materials are relatively shallow (less than 12 m [40 ft] in depth), surface collection trenches are sometimes used to collect landfill gas. The trenches are typically excavated 0.5 to 1 m (1.5 to 3 ft) into the waste. The trenches are then lined with a geotextile and filled with rock. A perforated pipe is often placed within the rock to increase flow capacity. The trenches should be spaced approximately 60 m (200 ft) apart and are usually not interconnected. Vertical vent pipes are located at the ends of the trench, or at high points, and spaced 60 m (200 feet) apart for passive vent trenches. Gas is removed from active vent trenches using a series of header pipes. This will allow for individual lines to be valved independently for future system control and balancing.

3.2.3.3. *Horizontal Trench Collection Systems.* An example of a horizontal trench collection system is shown in Figure 3.6. This type of collection system can be installed during the placement of waste in an active landfill and is; therefore, not applicable to the closure of old landfills.

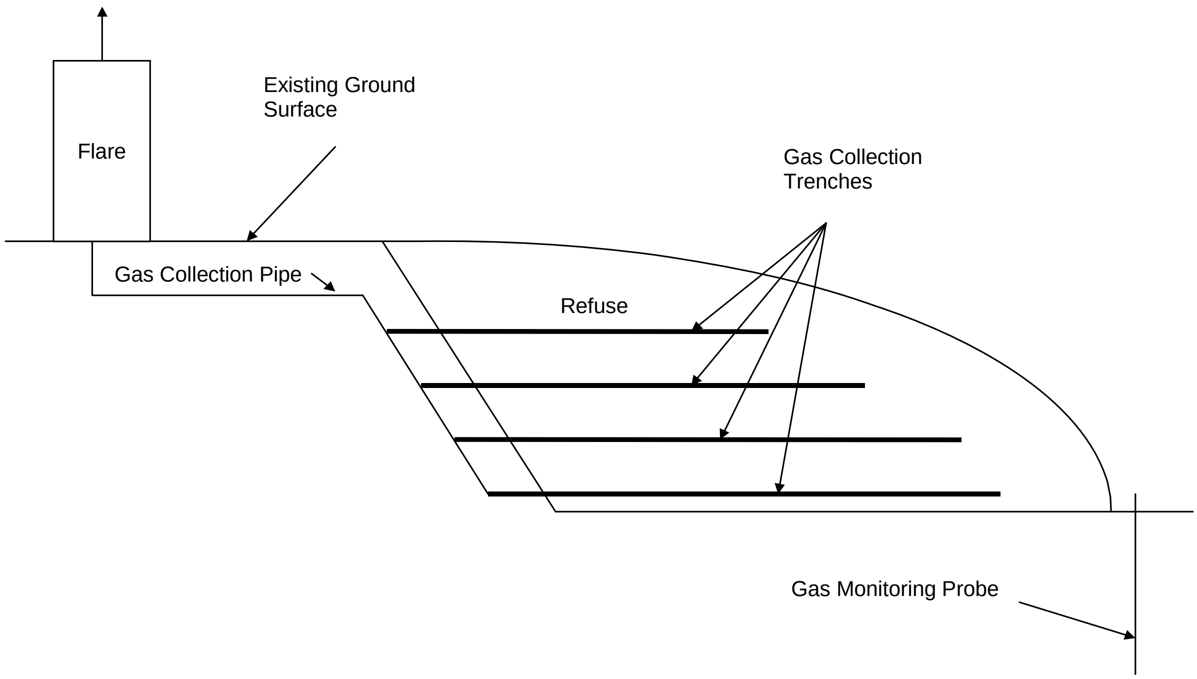

Figure 3.6. Horizontal Trench Collection System.

3.3. **Gas Monitoring Probes.**

3.3.1. *General.* Gas monitoring probes are used in conjunction with both active and passive systems to detect landfill gases that are migrating off-site. The regulatory compliance point is typically the property boundary. The maximum acceptable concentration of methane in the probes is typically 0.5 to 5 percent. Increased monitoring and/or modifications to the operating procedures of the landfill gas collection system are usually required if methane concentrations exceed acceptable levels. Gas samples may be also be analyzed for volatile organic contaminants to determine if there is a need to perform a soil gas survey to evaluate the soil vapor intrusion pathway.

3.3.2. *Design Considerations.* Gas monitoring probes are installed by placing a borehole into the ground to at least the same depth as the deposited waste. A 1.9 to 5.1 cm (0.75 to 2 inch) diameter perforated PVC pipe is placed into the hole and the space between the borehole wall and pipe is filled with sand or gravel. The sand and gravel layer should generally begin at least 1.5 m (5 feet) below the ground surface to reduce the potential for leakage of atmospheric air into the probe. A bentonite seal is placed above the filter pack and cement-bentonite grout is typically placed above the bentonite seal. Additional information on the design of gas monitoring probes can be found in EM 1110-1-4001, Soil Vapor Extraction and Bioventing.

3.3.2.1. It may be best to initially install probes deep enough to verify the water table and to assess stratification. Subsequent probes should then be placed above the water table in relatively permeable strata that is likely to be a good conduit for the movement of methane. It is advisable to install gas probes at various depths where the unsaturated layer adjacent to deep landfills is thick.

3.3.2.2. Probes are typically placed around the perimeter of the landfill at a maximum spacing of 150–300 m (500–1000 ft), although they may be closer, depending on site specific factors such as adjacent land use, soil properties, and migration potential. At some sites, probes may be closely spaced, every 30–60 m (100–200 ft), if there are buildings near the landfill. Each probe must be permanently marked or tagged with an identification number to ensure data is accurately recorded.

3.3.2.3. Probes may be driven into the ground if they are going to be used to monitor strata that are less than 15 feet below the ground surface.

3.3.3. *Monitoring Devices for Structures.* Basements and crawl spaces of buildings located near landfills are potential collection points for methane. Methane that collects in these confined spaces can create a potential explosion hazard. An explosimeter should be used to periodically monitor these confined spaces for explosive conditions. Federal and state regulations require that explosive concentrations of methane in structures on and off the landfill must not exceed 25% of the LEL (12.5% by volume). Corrective actions are often initiated if the monitor detects methane at concentrations as low as 10 percent of the LEL. In addition to monitoring for explosive gases, O_2 monitoring should be performed during entry into confined spaces.

Note that structures that actually are part of the LFG control system (e.g. piping, vaults) are excluded from this requirement.

3.4. **Cover Penetrations**

3.4.1. *General.* Penetrations through the landfill cover are required for gas vents, monitoring probes, and for other purposes. Geomembranes should be attached to the penetrating pipe in a way that ensures a watertight seal but still allows for movement from settlement or horizontal displacement. Geomembranes are generally attached to penetrations using a boot that attaches to the pipe.

3.4.2. *Design Considerations.* Most geomembrane manufacturers have their own typical penetration details. Therefore, in many cases, it is only necessary to show locations of the penetrations on the drawings and note that penetration details must be in accordance with approved geomembrane manufacturer's details. ASTM D 6497 - *Mechanical Attachment of Geomembrane to Penetrations or Structures* can also be referenced when specifying penetration requirements for geomembranes. Geosynthetic clay liner (GCL) penetration details should also be as recommended by the GCL manufacturer. Pipes that penetrate deeply into the waste material are likely to settle at a different rate and to a smaller magnitude than the adjoining landfill cover. The differential settlement between the pipe and the cover system creates stress concentrations at the boot connection that can tear the geomembrane away from the pipe. Slip couplings are typically used in this situation to allow differential movement while maintaining a watertight seal.

3.5. **Header Piping**

3.5.1. *General.* Header piping is used for active systems to transport gas from the collection wells to the flare. The piping system will typically have several branches. Multiple extraction wells are attached to each branch and valves are used to control the amount of flow coming from individual wells and branches. The number of low points in the header should be minimized and the flare should be located at a relative low point to aid in condensate collection within the header pipe. The piping can be placed on the landfill surface or it can be buried. In most instances, the header pipe should be buried to minimize the risk of damage from maintenance equipment and vandalism. Burying the header pipe also reduces the potential for blockage due to condensate freezing in the pipes. Buried header pipes are typically located above the geomembrane in the cover system. They should typically be a minimum of 150 mm (6 inches) of bedding material between the geomembrane and the header pipe. In some instances a marker tape has been installed approximately 150 mm (6 inches) above the pipe as a warning to maintenance workers who may be excavating into the landfill cover. Heat tracing can also be used to ensure condensate does not freeze in locations were the pipe cannot be installed below frost depth.

Above ground header pipes should only be considered where differential settlement of the landfill surface will result in reverse grades along the header pipe. Above ground pipe will need to be supported and sloped so that there is positive drainage to condensate collection pots. Placement of header pipe on the landfill surface is problematic in cold climates due to freezing condensate clogging the header. Above ground headers also make mowing and other maintenance activities more difficult.

3.5.2. *Design Considerations.*

3.5.2.1. *Pipe Material Options.* Header pipes are typically made of HDPE or PVC. PVC pipe is more susceptible to damage due to differential settlement than HDPE pipe because PVC is more rigid and brittle. It is also more vulnerable to ultraviolet (UV) radiation and low temperatures, 4°C (40^{o}F), than HDPE pipe. PVC pipe must be painted with UV inhibitive paint if it is to be exposed to direct sunlight. PVC header pipe is easier to install than HDPE pipe because it can be solvent welded. HDPE pipe must be heat fusion welded which is more time consuming and expensive.

3.5.2.2. *Pipe Slopes.* Condensate collection points should be located at low points in the header pipe system to prevent blocking of the pipe with condensate. Depending on local regulations, condensate is sometimes allowed to drip back into the waste either through the wellheads or a separate percolation drain where possible. Header pipes should be sloped according to the following criteria:

	In direction of gas flow	Opposite direction of gas flow
On Landfill	2% slope	4% slope
Off Landfill	1% slope	3% slope

3.5.2.3. *Pipe Size.* The header piping should be sized to provide for minimal head losses and additional capacity, should supplementary extraction wells be required at a later date. Pipes should be sized for approximately 25 mm (1 inch) of water column pressure drop per 30 m (100 ft) of pipe. This will give a good balance between blower and piping cost. Condensate will flow along the bottom of the header piping and is another consideration when sizing LFG header pipes. LFG velocity should be limited to 12 mps (40 fps) when the LFG and condensate are flowing concurrently so that the condensate will condense on the LFG header piping side walls. LFG velocity should be limited to 6 mps (20 fps) when condensate flow direction is opposite that of the LFG to avoid the condensate damming up and blocking the flow of LFG.

3.5.2.4. *Flexible Connections.* Flexible hoses are commonly used at wellheads, header and lateral pipes, pump stations, knock-outs, main lines, and at other connection points where there is expansion, contraction, and pipe movement due to landfill settlement. Flexible connections prevent excessive stress, which is one of the most common causes of gas conveyance line failure. Flexible hoses must be designed to withstand system pressures, and deterioration due to condensate and UV radiation. Flexible hose is typically constructed from a helix of stainless steel wire which is encapsulated within inner and outer ply's of polyester fabric and impregnated with silicone rubber that is UV-resistant. The hose is typically held in place with stainless steel bands. Flexible hose can also be welded or glued to some types of plastic pipe (PVC, CPVC, and ABS plastic pipe). The hose should be installed such that there are no low spots where condensate can accumulate and block the flow of gas.

3.6. **Valves**

3.6.1. *General.* Valves are utilized in LFOG collection systems for flow rate control and on/off control. A typical system will have a flow control valve on each extraction head. The valves may be manually controlled or automatically actuated by an electric or pneumatic power source. Pneumatic actuators tend to be simpler and less costly than electric actuators particularly for explosion-proof applications. For the closure of old landfills, LFOG collection systems often do not rely on automated control valves. The selection and layout of valves in the LFOG system should be carefully evaluated during the design process to ensure that the level of control provided in the system is consistent with projected O&M needs. The following considerations should be given when selecting valves.

3.6.1.1. *Temperature Range.* Valves must operate safely in the temperature and pressure range of the system. PVC valves are prone to failure at low temperatures, therefore, lined metal or

HDPE valves are preferable for cold-weather service. In some situations, valves must be insulated and/or heated to prevent condensation.

3.6.1.2. *Flow Capacity and Pressure Range.* The operating range of a control valve must match the flow control requirements of the application. A flow control valve functions by creating a pressure drop from the valve inlet to outlet. If the valve is too large, the valve will operate mostly in the almost closed position, giving poor sensitivity and control action. If the valve is sized too small, the upper range of the valve will limit flow.

3.6.1.3. *Strength and Durability.* Because LFG systems consist of multi-phase flow, valves and fittings should be constructed of stronger and more durable materials than might normally be required in single-phase water or gas service. The condensate can often form slugs of water drawn through the system at relatively high speed. This can result in a "water hammer" or impact loading on the valves and fittings.

3.6.1.4. *Frictional Losses.* Valves must not create excessive frictional loss when fully opened.

3.6.1.5. *Chemical Compatibility.* Valves must be chemically compatible with the liquid or air stream.

3.6.2. *Design Considerations.* Formulas and sizing procedures vary with valve manufacturer. Computations typically involve calculating a capacity factor (C_v), which depends on the flow rate, specific gravity of the fluid, and pressure drop. The designer calculates C_v at the maximum and minimum flow rates required. The calculated range of C_v values must fall within the range for the valve selected.

During the mechanical layout of the system, assure that the valves are accessible. Number and tag the valves. To avoid ambiguity, refer to the valves by number in the design and in the O&M manual. The following is a brief description of several valves commonly employed for LFOG collection and treatment systems:

3.6.2.1. *Gate Valve.* Gate valves are primarily designed to serve as isolation valves. In service, these valves generally are either fully open or fully closed. When fully open, gas flow through the valve is in a straight line with very little resistance. As a result, the pressure loss through the valve is small. Gate valves are frequently used at well heads to control flow from individual wells.

3.6.2.2. *Butterfly Valve.* Butterfly valves are used for both on/off and throttling applications at well heads and for other applications. The butterfly valve is characterized by fast operation and low pressure drop. Flow is controlled with a rotating disk or vane. This valve has relatively low friction loss in the fully open position. Butterfly valves can more accurately control a flow rate in gas or multi-phase service than gate valves.

3.6.2.3. *Globe Valve.* Used for on/off service and clean throttling applications, this valve controls flow with a convex plug lowered onto a horizontal seat. Raising the plug off the seat allows for fluids to flow through. Globe valves can more accurately "pinch" or control a flow rate in gas or multi-phase service than butterfly valves.

3.6.2.4. *Ball Valve.* Also used primarily for on/off control and some throttling applications, the ball valve uses a rotating ball with a hole through the center to control flow. Ball valves can be operated quickly and result in negligible resistance to flow when fully open.

3.6.2.5. *Diaphragm Valve.* A multi-turn valve used to control flow in both clean and dirty services. The diaphragm valve controls flow with a flexible diaphragm attached to a compressor and valve stem.

3.6.2.6. *Needle Valve.* A multi-turn valve used for precise flow control applications in clean services, typically on small diameter piping. Needle valves have relatively high frictional losses in the fully open position.

3.6.2.7. *Check Valve.* Check valves are used to allow flow in one direction only. Check valves are sometimes needed between the well and the pump to prevent air from being drawn backward when the pump is shut off. Under high vacuum, this can affect a variety of in-line readings, particularly if a carbon canister is being used for air treatment.

3.6.2.8. *Sample Valve.* Quick connect sample valves are used on gas monitoring probes and well heads to check pressure or gas constituent concentrations.

3.7. **Well Heads.** Well heads for passive gas vents are typically configured to prevent precipitation and wildlife from entering the well. Wellheads for active well systems typically include control valves to increase and decrease the flow of gas from individual wells and flexible connections to compensate for differential movement between landfill gas wells and header pipes. The well head will also include sampling ports to monitor gas concentrations, temperature, velocity, and pressure. Specialty companies have created data collection ports that can be easily attached at each well head to allow easy collection of this data. Portable measuring equipment is attached to the measuring ports to collect the required data.

3.7.1. *Flow Rate Measurement.* Pitot tubes and orifice plates are the two most common methods of measuring flow at a well head of a landfill gas collection system.

3.7.2. *Orifice Plate.* An orifice plate is a thin plate with a circular hole in the center (See Figure 3.7). The plate is placed within a pipe perpendicular to the direction of gas flow. Orifice plates are used to determine gas flow rate by measuring the differential pressure across the orifice plate. They are generally less expensive to install and manufacture than the other commonly used differential pressure flow meters; however, nozzle and venturi flow meters have the advantage of lower pressure drops. Equations for orifice meters have the advantage of no Reynolds Number upper limit for validity. An orifice flow meter is typically installed between flanges connecting two pipe sections. Gas flow calculations include an expansion factor. The expansion factor accounts for the effect of pressure change on gas density as gas flows through the orifice.

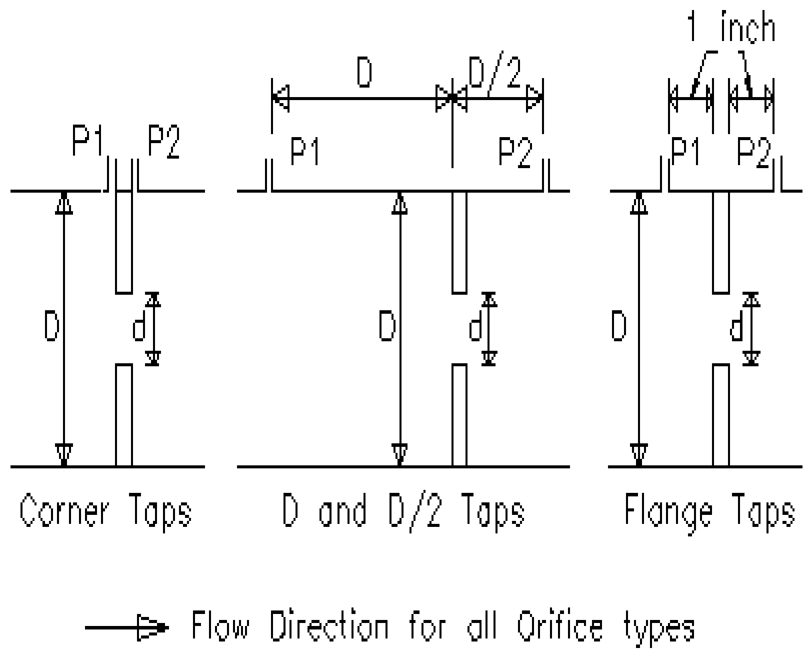

Figure 3.7. Orifice Plate Flow Measurement Device.

3.7.3. *Pitot Tube.* A pitot tube is used to measure velocity based on a differential pressure measurement as shown in Figure 3.8. The Bernoulli equation models the physical situation very well. A pitot tube can also give an estimate of the flow rate through a pipe or duct if the pitot tube is located where the average velocity occurs. The average velocity times the pipe cross sectional area equals the flow rate. Often, pitot tubes are negligently installed in the center of a pipe. This gives the velocity at the center of the pipe, which is usually the maximum velocity in the pipe, and could be twice the average velocity. See ACGIH® Industrial Ventilation: A Manual of Recommended Practice for additional information on the use of Pitot tubes.

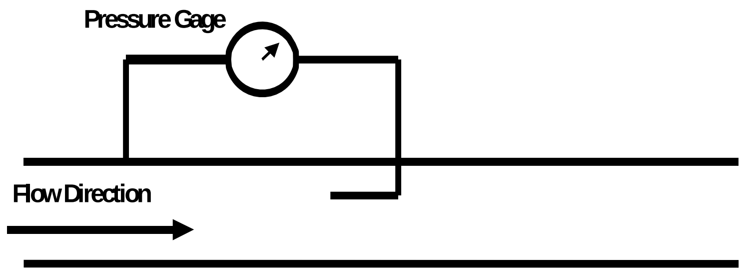

Figure 3.8. Pitot Tube Flow Measurement Device.

Bernoulli's equation is used to estimate flow velocity based on pressure measurements from a Pitot tube:

$$V = [2\,(P_T - P_S)/\rho]^{0.5}$$

where:

V = fluid velocity
P_T = total pressure
P_S = static pressure
ρ = fluid density.

3.8. **Header System Layout.**

3.8.1. *General.* A header system can be constructed in three general configurations: branches, loops, or as a matrix. These layout options are shown in Figure 3.9. Branched systems consist of individual wells attached to a blower through the use of a header pipes and larger trunk lines. Branched systems are fairly common on small landfills where there are a limited number of wells. Looped systems ring the landfill and have the advantage of allowing gas to be pulled from an individual well from more than one direction, bypassing clogs in the header line. Looped systems will often incorporate branches off of the main loop to allow collection of gas from regions of the landfill that are not adjacent to the loop. The design objectives of the header system are as follows:

- Create sufficient vacuum and flow from each extraction well to collect all landfill gas and prevent the off-site migration of gas.
- Move the gas through the header system to the blower and flare.
- Accomplish the first two objectives with the lowest possible capital and operating expenditures.

Pressure losses in the piping system are the result of friction losses and dynamic losses. Friction losses occur as gas flows through the header pipes. Dynamic losses result from things such as changes in flow direction (elbows and tees), pipe constrictions, valves, filters, knock-out pots, and other restrictions within the piping network. The total pressure loss is the sum of the friction and dynamic losses.

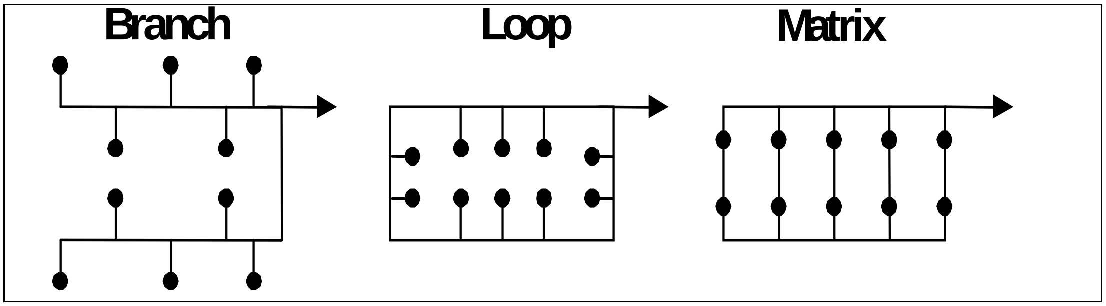

Figure 3.9. Header Layout Options.

3.8.2. *Design Considerations.* It is important to consider overall system pneumatics prior to designing and selecting individual system components. A suggested approach is briefly summarized below (Brown and Clister 1993):

3.8.2.1. *Step 1.* Determine the size and depth of the landfill.

3.8.2.2. *Step 2.* Determine the type of waste within the landfill and its associated gas generation rate.

3.8.2.3. *Step 3.* Estimate the Radius of Influence (ROI) and based on this ROI, layout the gas extraction wells and the header pipes.

3.8.2.4. *Step 4.* Develop a relationship for vacuum level versus airflow in the subsurface.

3.8.2.5. *Step 5.* Calculate the friction loss for the system components and piping for a range of flow rates.

3.8.2.6. *Step 6.* Develop a "system" curve by adding the frictional losses calculated in steps 4 and 5.

3.8.2.7. *Step 7.* Select a blower with an appropriate blower curve.

3.8.2.8. *Step 8.* Predict the flow rate and vacuum level from the simultaneous (graphical) solution of the blower curve and the system curve.

3.8.2.9. *Step 9.* Perform a network pressure analysis using the assumed well layout and equipment. Determine if the proposed system provides adequate vacuum and flow to all portions of the landfill.

3.8.3. *Subsurface Losses.* Subsurface losses are a function of the following:

- Waste permeability.
- Radius of influence of the well.
- Depth of waste.
- Gas extraction rate.
- Gas generation rate.

For large municipal solid waste landfills, subsurface losses can most accurately be quantified by performing pump tests. These tests determine the required vacuum needed to maintain a given flow rate. However, for older landfills such as those found at military installations, pump tests are not commonly performed as part of the design process. If pump tests are not performed, subsurface losses will need to be estimated based on existing conditions and past experience of the designer. Typically, the extraction well vacuum can be assumed to be 125 to 250 mm (5 to 10 inches) of water column.

3.8.4. *Pipe Losses.* Head loss through the header system components can be predicted for a range of flow rates. The most common method of predicting friction losses in straight pipes is to use the Darcy-Weisbach equation for incompressible fluids:

$$h_f = f\,(L/d)\,(v^2/2g)$$

where:

h_f = friction loss [ft (m) of water]
f = friction factor [dimensionless (dimensionless)]
L = pipe length [ft (m)]
d = inside pipe diameter [ft (m)]
v = average velocity of the flow [ft/s (m/s)]
g = gravitational acceleration [32.16 ft/s² (9.807 m/s²)]

Use of Darcy-Weisbach for gases is limited to systems with less than 10% compression without correction. The friction factor f is a dimensionless number that has been determined experimentally for turbulent flow and depends on the relative roughness of the interior of the pipe and the Reynolds number. Tables and charts have been developed to predict friction losses for a range of pipe materials and diameters.

3.8.5. *Losses in Valves and Fittings.* There are two primary methods for estimating head losses through valves and fittings:

- Look up k values in tables (where $k = f\,L/d$ and, therefore, $h_f = kv^2/2g$).

- Use tabulated values of equivalent length of straight pipe. For example, the resistance in a 150 mm (6 inch) standard elbow is equivalent to that of approximately 5 meters (16.5 feet) of 150 mm (6 inch) straight pipe.

3.8.6. *Losses at Flare Station.* Condensate collection tanks, flame arrestors and other equipment will typically result in applied head losses of around 125 mm (5 inches) of water column. The flare itself will exert a backpressure on the outlet side of the blower. This backpressure is typically around 250 mm (10 inches) of water column.

3.8.7. *System Analyses.* The friction losses from the subsurface, the straight pipe lengths, and the valves and fittings are added together to obtain the total friction loss at a given vacuum level. This calculation is repeated for several flow rates to establish a system curve. Note that these calculations are performed assuming that the valves are fully open.

The blower curve is then superimposed on the system curve. A specific blower should be selected based on mechanical, electrical, and pneumatic considerations. The blower curve is negatively sloped and the system curve is positively sloped. The predicted flow rate and vacuum level occur at the intersection of the two curves, representing the simultaneous solution of two equations.

The predicted flow rate must exceed the design flow rate to allow flow control of multi-well systems by valves located at individual wellheads. This adjustment causes an increase in vacuum level at the blower and a decrease in the total flow rate as shown in Figure 3.10. The designer must verify the new flow rate and pressure are within the operating range of the blower. Therefore, the operating point must be on the blower curve above the intersection of the blower curve and the system curve. For complex piping networks, it would be worthwhile to acquire software designed for this application.

3.8.8. *Simplified Pneumatic Design Procedure.* The following is a simplified design procedure taken from CES-Landtec Landfill Gas System Engineering Design Seminar courseware and can be used to estimate system vacuum and pressure requirements for the blower.

3.8.8.1. *Problem.*

3.8.8.1.1. Estimate the following:

Total system flow _______ cubic feet per minute (cfm)
Fan pressure _______ Inches of water column (in. w.c.)

3.8.8.1.2. Based on the specified flow and pressure of the gas collection system, select the "longest" pipe run (or path with highest resistance to gas flow) and calculate the Total Pressure Drop (TPD) from blower to extraction well:

Total pressure drop or fan pressure required = pipe friction + fitting losses + applied head losses

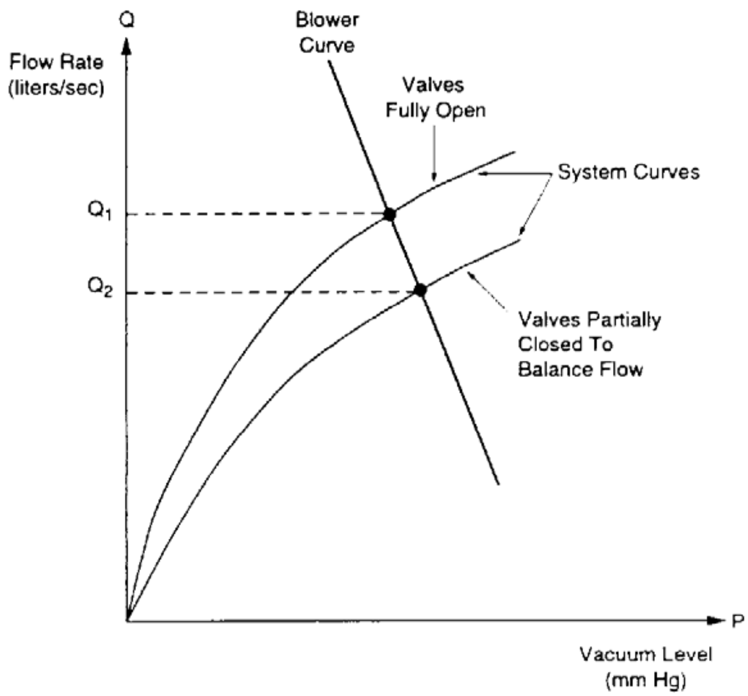

Figure 3.10. Typical Pneumatic Analysis.

3.8.8.2. *Determine Header Pipe Friction Loss.* Pipe friction can be calculated by multiplying the effected length of pipe (feet) times the Darcy friction factor found on the Moody Diagram. The following equation represents Darcy's Friction Loss:

$h_f = f\,(L/d)\,(v^2/2g)$

where:

h_f = friction loss [ft (m) of fluid]
f = friction factor [dimensionless (dimensionless)]
L = pipe length [ft (m)]
d = inside pipe diameter [ft (m)]
v = average velocity of the flow [ft/s (m/s)]
g_c = gravitational acceleration [32.16 ft/s² (9.807 m/s²)].
ΔP = $f\,(\rho_g/\rho_w)\,(L/d)\,(v^2/2g)$

where:

ΔP = pressure drop [in w.c./100 ft of pipe]
ρ_g = gas density [lb_m/ft^3]

ρ_w = water density [62.4 lb_m/ft^3]
L = 100 ft of pipe

and

$\Delta P = f\,(\rho_g/62.4\ lb_m/ft^3)\,(100/d)\,(v^2/2 * 32.16\ ft/s^2)$
$\Delta P = f\,(\rho_g/(62.4 * 2 * 32.16\ s^2\ lb_m/ft^2))\,(L/d)\,(v^2)$
$\Delta P = 0.000249\ s^2\ lb_m/ft^2\ f\,(\rho_g)\,(L/d)\,(v^2)$
1 pound-force/square foot = 0.1922216 inch of water [4 °C]
$\Delta P = 0.004789$ in w.c./100 ft of pipe $f\,(\rho_g L\, v^2/d)$

Total $\Delta P_{friction}$ = Header Friction Loss + Branch Friction Loss

3.8.8.2.1. Select length ________ (ft) of affected header pipe (L)

3.8.8.2.2. Obtain specified blower flow rate (Q) _________(cfm)
3.8.8.2.3. Determine pipe internal diameter as _______ in. or (_______ ft)

3.8.8.2.4. Use Continuity Equation (Q = vA) to calculate velocity as ________ (linear ft/min) or _________ (ft/s). Where multiple branches of header pipe exist, the flow must be estimated in each branch.

3.8.8.2.5. Calculate Reynolds Number (N_{RE}) using the following equation:

$$N_{RE} = \frac{Dv\rho}{\mu_e}$$

where:

D = pipe diameter (ft)
v = fluid velocity (ft/s)
ρ = fluid density (lb_m/ft^3)
μ_e = absolute viscosity (lb_m/ft s).

Reynolds Number =__________ Determine if the flow is turbulent or not. .

3.8.8.2.6. Determine the relative roughness of pipe materials (ε/D) as _____________

3.8.8.2.7. Use Moody Chart to determine the Darcy friction factor by determining the relative roughness:

f = _______________(estimated)

Substituting into Darcy:

$$\Delta P = \frac{(\rho)(f)(100)(v)^2(27.7)}{(144)(D)(64.4)}$$

ΔP = _______ (in. w.c.) per 100 ft of pipe

Total friction loss for header pipe section = (Header pipe length _____ft / 100) x _______ΔP (in. w.c.) = _______in w.c.

3.8.8.3. *Determine Branch Pipe Friction Loss*

3.8.8.3.1. Select length ________ (ft) of affected branch pipe (L)

3.8.8.3.2. Obtain specified branch flow rate (Q) _________(cfm)

3.8.8.3.3. Determine pipe internal diameter as _______ in. or (_______ ft)

3.8.8.3.4. Use Continuity Equation (Q = vA) to calculate velocity as ________ (linear ft/min) or _________ (ft/s). Where multiple branches exist, the flow must be estimated in each branch.

3.8.8.3.5. Calculate Reynolds Number (N_{RE}).

N_{RE} = __________ Verify if the flow is turbulent or not.

3.8.8.3.6. Determine the relative roughness (ε/D) as _____________

3.8.8.3.7. Use Moody Chart to determine the Darcy friction factor using the appropriate relative roughness curve:

f = _______________(estimated)

Substituting into Darcy:

$$\Delta P = \frac{(\rho)(f)(100)(v)^2(27.7)}{(144)(D)(64.4)}$$

ΔP = _______ (or psi) per 100 ft of pipe

Total friction loss for branch pipe section = (header pipe length _____ft / 100) × ________ΔP (in. w.c.) = _______in. w.c.

Total Friction Loss = Header ______ + Branch ______= ___________________(in. w.c.)

3.8.8.4. *Calculate Valve and Fitting Losses.* Locate all valves (ball, globe, angle etc.) and fittings (elbows, tees, reducers, etc.), which are in the "longest run" of piping and are points of resistance against flow from the extraction well to the blower.

Header Pipe Section (Darcy ΔP = _______in. w.c./100 ft of pipe):

Fitting Type	**No.**	**Size**	**Eq. Leng.**	**ΔP**
Gate Valve	____	____	_________	_______
Ball Valve	____	____	_________	_______
Check Valve	____	____	_________	_______
90° Standard Elbow	____	____	_________	_______
45° Standard Elbow	____	____	_________	_______
Standard Tee	____	____	_________	_______

Branch Pipe Section (Darcy ΔP = _______in. w.c./100 ft of pipe):

Fitting Type	**No.**	**Size**	**Eq. Leng.**	**ΔP**
Gate Valve	____	____	_________	_______
Ball Valve	____	____	_________	_______
Check Valve	____	____	_________	_______
90° Standard Elbow	____	____	_________	_______
45° Standard Elbow	____	____	_________	_______
Standard Tee	____	____	_________	_______

Compute the pressure drop from these sources using the following methods:

3.8.8.5. *Pressure Drop Due to Fittings.* Using PVC or HDPE pipe manufacturer's data, obtain "equivalent length of straight pipe" data for fitting types and sizes used in the "longest run." By multiplying the Darcy friction factor for the effected section of piping (i.e. the header or the branch, times the effected fitting's "equivalent length of straight pipe") the pressure drop across the fitting can be computed.

What follows is an example. Given: ΔP = 0.654 in. w.c./100 ft of pipe*

$\rho = 0.065\ lb_m/ft^3$, $\mu_e = 8.14 \times 10^{-6}\ lb_m/ft{\cdot}s$

* Computed using Q = 800 cfm, D = 0.665 ft.

for smooth plastic pipe. Find the pressure drop due to two 8-inch 90^o elbows and three 8-inch tees in the header pipe section. The solution is as follows.

3.8.8.5.1. Obtain pipe manufacturer's "equivalent length of straight pipe" data for 8-inch elbow and 8-inch tee:

For 8-inch, 90^o elbow, equivalent length = 33.3 ft

For 8-inch tee, with flow through run, equivalent length = 16.5 ft.

3.8.8.5.2. Using ΔP = 0.654 in w.c./100 ft of pipe for Q = 800 cfm in 6 in (0.665 ft ID) pipe.

Δp_{elbows} = (0.654 in. w.c.) x (33.3 ft/100 ft) × 2 = 0.436 in. w.c.

Δp_{tees} = (0.654 in. w.c.) x (16.5 ft/100 ft) × 3 = 0.323 in. w.c.

3.8.8.5.3. Compute $\Delta p_{fittings} = \Delta p_{elbows} + \Delta p_{tees}$

$\Delta p_{fittings}$ = (0.436 in. w.c.) + (0.323 in. w.c.) = 0.759 in. w.c.

3.8.8.6. *Pressure Drop Due to Valves.* The previous method used for fittings can also be used for valves if equivalent length data is available. If equivalent length data is not available the pressure drop due to valves can be computed using the following equation:

$$\Delta P_{valve} = \left(\frac{\rho}{62.4}\right)\left(\frac{7.48\,Q}{C_v}\right)^2$$

where:

ρ = fluid density (lb_m/ft^3)
Q = flow through valve (ft^3/min)
C_v = valve or fitting coefficient

C_v can usually be obtained from the valve manufacturer's data. If the fitting coefficient must be computed the following may be used:

$$C_v = \frac{29.9\,d^2}{\sqrt{K}}$$

where:

C_v = valve or fitting coefficient
d = pipe diameter (in.)

K = resistance coefficient*

The following is an example. Given are the following: Q = 800 cfm; ρ = 0.065 lb_m/ft^3; d = 8 inches; K = 106.5, 62.4 = lb_m/ft^3 for water Find ΔP_{valve}. Solution:

$$\Delta P_{valve} = \left(\frac{0.065\ lb_m/ft^3}{62.4}\right)\left(\frac{(7.48)(800ft^3/\min)}{\frac{29.9\ (8\ inch)^2}{\sqrt{106.5}}}\right)^2$$

ΔP_{valve} = 1.09 in. w.c.

3.8.8.7. *Calculate/Determine Applied Head Losses.* Applied head losses for gas control systems usually consist of the following:

- Extraction Well Vacuum _______ in. w.c. (typical: 5–10 in. w.c.)
- Flare Backpressure _______ in. w.c. (typical: 10 in. w.c.)
- Inlet Scrubber Vessel _______ in. w.c. (typical: 2–5 in w.c.)

Total Applied Head Loss _______ in. w.c.

3.8.8.8. *Compute Total Head Loss from Extraction Well to Flare.*

- Pipe Friction Head Losses _______ in. w.c.
- Fitting and Valve Losses _______ in. w.c.
- Applied Head Losses _______ in. w.c.

Total Pressure Drop _______ in. w.c.

3.9. **Condensate Collection**

3.9.1. *General.* An important element in the design of a gas collection system is condensate management. Condensate is formed when warm LFG cools during transport or processing. LFG is typically warm and saturated when extracted from the moist environment of a landfill. As the gas travels through the header pipes, it cools, which reduces its moisture holding capacity. The quantity of condensate generated in a LFG collection system is a function of how much LFG is being extracted, the vacuum or pressure being exerted on the LFG, and the magnitude of the temperature change. To prevent this water from blocking the header lines, low points in the piping system should have condensate knock-out tanks. A knock-out tank is also typically located within the flare station to help prevent condensate from damaging the blower and other equipment located in the

* Normally provided by fitting/valve manufacturer.

flare station. Knock-out tanks are specifically designed to promote the formation of liquid droplets and to separate these droplets from the gas flow. Knock-out tanks are periodically pumped out. On large landfills, condensate collection can be automated with pumps and a piping system that carries the condensate to a central location where it can be stored and treated.

When laying out the header piping system, condensate collection should be an important consideration. If feasible, the header piping can follow surface water management berms. This will facilitate installation and maintenance of the header lines. Settlement of the waste must also be considered when laying out the header system. Excessive settlement may result in reverse grades that trap condensate and plug the header lines. Additional condensate collection points should be placed in areas where a large amount of settlement is anticipated or where header lines have very little slope.

3.9.2. *Design Considerations.* Some reasonable assumptions may be made when estimating condensate generation:

- LFG temperature at the wellhead is the warmest.
- The header pipe is installed below the frost line.
- LFG temperature depends on the distance traveled in the buried header pipe and the thermal conductivity of the header pipe.
- LFG is completely saturated with water vapor.

The quantity of LFG condensate will vary throughout the year. Typically, during the winter, condensate formation will be at its highest. A psychometric chart is a graphical representation of the thermodynamic properties of moist air. These tables can also be used to provide information on the amount of moisture in landfill gas even though LFG is generally a combination of methane and carbon dioxide. The following set of example calculations demonstrates how to estimate the quantity of condensate that will be generated.

3.9.2.1. *Sample Calculation—Condensate Quantity.* Estimate the rate of condensate generation for a section of header pipe of a landfill gas extraction system. The flow rate within the header pipe is 500 cfm (236 L/s). The system is under a vacuum of 40 inches of water (91.4 kPa). This is equivalent to an absolute pressure of 0.9 atmospheres. The average ambient temperature of the soil surrounding the header pipe is 50^{o}F(283 K). The solution is as follows:

Assume the gas extracted from the landfill is 50% methane and 50% carbon dioxide and is at 100% relative humidity. Assume the gas temperature within the pipe drops from 90^{o}F (305 K) as it exits the landfill to 70^{o}F (294 K) as it travels through the header pipe. The water holding capacity of the landfill gas will drop as the temperature of the gas drops and can be estimated from a psychrometric chart.*

Conc. of water vapor = 0.030 kg water/kg landfill gas (at 305 K)

Conc. of water vapor = 0.015 kg water/kg landfill gas (at 294 K)

Subtracting gives:

Potential Condensate = 0.015 kg water/kg landfill gas

The ideal gas law can be used to estimate the density of the gas passing through the header pipe:

Density = $P\,M/R_U T$

where:

P = absolute pressure within header pipe
M = molecular weight of landfill gas
= 0.5 (molecular weight methane) + 0.5(molecular weight of carbon dioxide)
= 0.5 (16) + 0.5 (44) = 30 kg/kg-mole
R_U = Universal gas constant = 0.0821 L-atm/g-mole K
T = temperature.

Density = $P\,M/R_U T$ = [(0.9 atm) × (30kg/kg-mole)] / [(0.0821 L-atm/ g-mole K) × (294 K) × (1,000 g-mole/kg-mole)]
Density of landfill gas = 1.12×10^{-3} kg/L

The flow rate times the concentration of the condensate yields the following condensate generation rate:

(0.015 kg water/kg LF gas) × (1.16×10^{-3} kg/L) × (236 L/s) × (86,400 s/day) × (1 L/kg) = 356 L/day

3.9.2.2. *Condensate Pumps.* Several options exist for dealing with condensate. Condensate generated can be drained back into the landfill, if allowed by the approving regulatory agency, the. If the condensate must be collected and treated, two options exist: 1) The condensate can be collected in several large tanks located throughout the header system; or 2) the condensate can be

* Most psychometric charts are created for higher pressures than are typically found in the header pipes of a LFG collection system. However, using these charts will generally not introduce large error when estimating condensate generation.

periodically removed from several smaller collection tanks using pumps and header pipes. In this scenario, the condensate will typically be stored in a larger tank prior to off-site disposal.

The condensate generation rate must be estimated to determine the condensate pump required. Typical condensate sump pumps are rated from 10-30 gpm with 1 to 2 inch discharge piping. The preferred design velocity in the discharge is approximately 5 feet per second (between 2 and 8 feet per second). Friction losses in the piping are estimated by the Hazen-Williams method, valid only for water at ordinary temperatures (40 to 75 ^oF).

$$h_f = L\,(V / K\,C\,R_h^{0.63})^{1.852}$$

$$h_f = L\,(V / 1.318\,C\,R_h^{0.63})^{1.852} \text{ (English units)}$$

where:

h_f = frictional head loss (ft H_2O)
L = pipe length (ft)
V = velocity (2 - 8 ft/s)
K = unit conversion factor = *1.318*
C = Hazen-Williams roughness coefficient (80 – 150).
R_h = hydraulic radius (ft) = d (in)/48

Substituting:

$$V = Q / 448.8312 / \quad (d/24)^2$$
$$V = 0.4085\,Q / d^2$$

where:

Q = flow (gallons per minute)
d = inside diameter of pipe (inches).
h_f = $L\,[(0.4085\,Q / d^2) / 1.318\,C\,(d/48)^{0.63}]^{1.852}$
h_f = $10.458\,L\,Q^{1.852} / C^{1.852}\,d^{4.87}$ (English units)

$$h_f = L\,(V / K\,C\,R_h^{0.63})^{1.852}$$

$$h_f = L\,(V / 0.8492\,C\,R_h^{0.63})^{1.852} \text{ (SI Units)}$$

where:

h_f = frictional head loss (m H_2O)
L = pipe length (m)
V = velocity (0.61 - 2.44 m/s)
K = unit conversion factor = *0.8492*
C = Hazen-Williams roughness coefficient (80 – 150).

R_h = hydraulic radius (m) = d (m)/4

Substituting:

V = $Q / \pi(d/2)^2$
V = $1.2732\, Q / d^2$

where:

Q = flow (m^3/s)
d = inside diameter of pipe (m).

h_f = $L\,[(1.2732\, Q / d^2) / 0.8492\, C\, (d/4)^{0.63}]^{1.852}$
h_f = $10.672\, L\, Q^{1.852} / C^{1.852}\, d^{4.87}$ (SI Units)

3.9.2.2.1. Determine if longest run of condensate pipe is adequately sized, such that total head loss Δh_{total} is 10 percent of the condensate sump pump's specified pressure.

3.9.2.2.2. Use the Hazen-Williams equation to estimate head loss.

3.9.2.2.3. Compute the total head loss from pump to receiver tank (assume 20% loss due to fittings):

Δh_{total} = (h_f _____ ft/100 ft of pipe) ×(Total Length of Run (ft) + 20%)

3.9.2.2.4. Determine if Δh_{total} is approximately 10% of specified pump pressure.

Δh_{total} ______ psia < / = / > .10 ×h_{pump} _________ psia

3.9.2.2.5. Other design considerations include the following:

- Sumps should be located at lowest elevation with respect to gas header and branches from which condensate will be collected.
- All condensate pipes should have at least a 3 percent slope (if possible) to promote drainage.
- Condensate pipe should be run with air supply lines and gas collection lines to provide better access for maintenance and protection of pipe (if PVC or HDPE is used).
- Most condensate collection system sump pumps use compressed air versus electric powered. If a compressed air system is used, air lines and air compressors will need to be sized as part of design process.
- Condensate collection systems are normally discharged to regional waste water treatment systems with an amendment to the operator's NPDES or sewer use permit. However, depending on the amount of condensate and its characteristics, pretreatment

may be necessary prior to discharge (to a sewer system or navigable waterway). Several skid mounted treatment systems are commercially available.

3.10. **Design Procedures for Passive Collection Systems**

3.10.1. *General.* The purpose of a passive gas collection system is to prevent the build-up of gas pressure within the landfill to maintain the stability of the landfill cover and to prevent the off-site migration of landfill gas. Passive collection systems can be designed as blankets, wells, or trenches. Strict design procedures are often not employed to design passive systems because they are typically placed on old and/or small landfills where the potential for landfill gas generation is small. Instead of using strict design procedures, rules of thumb are commonly applied in the design of passive gas collection systems.

3.10.2. *Passive Blanket Collection Systems.* Because blanket gas collection systems do not penetrate down into the waste layer, they are less effective than well systems in preventing the off-site migration of landfill gas. However, blanket gas collection systems are effective at preventing the buildup of pressure beneath a cover system. Granular soil layers used as gas collection blankets are typically 305 mm (12 inches) in thickness. If a geonet drainage layer is used it will typically be a geocomposite with a geotextile attached to one or both sides of the geonet. The geotextiles attached to the geonet prevent soil and waste from entering the geonet. The geotextiles also increase the frictional resistance at the drainage layer interfaces. Geotextiles can also be used as the gas collection layer if the anticipated production of LFG is very small and the normal stresses acting on the geotextile are small. Thiel (1998) recently reported air transmissivity values for geotextiles. The following are the average flux values reported:

Geotextile Type	**Transmissivity**
540 g/m^2 (16 oz/yd^2)	
Wet	9.74×10^{-7} m^3/s/m
Dry	6.50×10^{-6} m^3/s/m
680 g/m^2 (24 oz/yd^2)	
Wet	2.81×10^{-6} m^3/s/m
Dry	1.87×10^{-6} m^3/s/m

3.10.2.1. *Design Procedures for Passive Blanket Collection Systems.* If there is a potential for the build-up of gas pressure beneath a geomembrane barrier layer, slope stability becomes a concern and a more rigorous design procedure should be implemented. The general steps required when considering gas pressure in the design of a passive landfill gas collection blanket are as follows:

- Estimate the maximum gas flux that needs to be removed from below the landfill cover.

- Perform slope stability analyses to estimate the gas pressure at which slope instability will result.
- Design a vent system below the cover that will evacuate the assumed gas flux and prevent the build-up of gas pressure beneath the geomembrane.

If the gas-collection layer is a granular material, it is reasonable to assume that the granular material will be holding a certain amount of capillary water either due to rain during construction, or from condensate collecting beneath the barrier layer. The reduction in gas permeability due to partial saturation of the layer can be estimated using the Brooks and Corey relationship. Based on preliminary experimentation, Thiel (1998) makes the following recommendations on the field-gas permeability of granular collection layers:

- For fine sands containing less than 10–15 percent fines, the field-gas permeability can be taken as the dry-gas permeability reduced by a factor of 5 to 10 to account for the presence of field-moisture.
- For clean medium and coarse sands, the field-gas permeability can be taken as the dry-gas permeability reduced by a factor of 2 to account for the presence of field-moisture.
- For rock gas collection layers, there will be little or no measurable reduction in permeability due to water retained within the pore spaces of the rock.

Calculations and experimental evidence from the literature suggest that landfill gas flow rates in passive blanket collection layers are generally expected to be laminar and Darcy's law applies.

3.10.2.2. *Maximum Acceptable Gas Pressure.* Thiel (1998) outlines a design methodology for estimating the slope stability for the case where landfill gas pressure builds up beneath the barrier layer. The following equation can be used to estimate the maximum acceptable gas pressure beneath the geomembrane barrier layer:

$$\text{Factor of Safety} = [(H\gamma \cos B - \mu_g) \tan \phi] / H\gamma \sin B$$

where:

H = height of cover soil (m)
γ = cover soil density (kN/m^3)
μ_g = landfill gas pressure (kPa)
B = slope angle.

3.10.3. *Design Considerations for Passive Well Collection Systems.* Passive gas collection wells are typically spaced approximately 60 meters (200 feet) apart, i.e.: 1 per 0.4 hectare (1 per acre). Additional wells will be required if perimeter monitoring probes indicate the methane concentration exceeds the regulatory limit for the site. Vertical risers should also be located at high points in the collection system within the landfill.

3.11. **Design Procedures for Active Well Collection Systems**

3.11.1. *General.* Spacing of LFG collection wells for active systems is highly dependent on site-specific variables such as waste density, waste moisture content, waste thickness, well design, and cap configuration. The following methods have been used to determine the well spacing of LFG collection systems:

- Cylinder method. This is a popular approach used by numerous consulting firms and involves estimating the amount of landfill gas being produced within the radius of influence (ROI) of an extraction well.
- Field pump tests. The designer uses pump test results to obtain data to identify the site-specific zone of influence of extraction wells.
- Prescriptive/regulatory criteria. Some states have regulatory requirements related to gas vent spacing. For example, the Wisconsin Department of Natural Resources requires all designs to use a maximum of 150-foot radius of influence unless a pump test is conducted.
- Rule of thumb criteria. This method relies on past experience to aid in the layout of the gas collection wells. Some designers correlate gas vent well spacing to the depth of the waste. Typically, wells are spaced no farther apart than 3 times the depth of the waste with a maximum acceptable spacing of 300 feet.

Whichever design method is used, the designer must ensure gas is collected from the entire area of the landfill and off-site migration is prevented.

3.11.1.1. *Cylinder Method.* This approach assumes all gas generated from within a cylinder of a specified radius is removed by the well and that no leakage from the atmosphere enters the landfill (Emcon, 1980). This method is most appropriate for landfills with low-permeability covers. Figure 3.11 shows a typical layout for wells designed using the cylinder method. The following equations can be used to apply the cylinder method:

3.11.1.1.1. *Flow Rate for Entire Landfill.* The following equation can be used to estimate the total amount of gas being generated from within a landfill:

$$Q_{\text{tot}} = (V)(D)(G)/(\text{percent methane in gas})$$

where:

V = volume of waste
D = density of waste
G = methane production rate.

Typically, methane represents approximately 30 to 55 percent of the total volume of gas generated from a landfill. Since the G term is only an estimate of the amount of methane generated, to determine the total landfill gas flow rate, divide (V)(D)(G) by the percent methane.

3.11.1.1.2. *Determine Flow Rates from Each Well (Cylinder Method).* The flow rate from individual wells can be determined by assuming a radius of influence and estimating the amount of gas generated from within this radius using the methane production rate discussed above:

$$Q = \pi\,(R^2 - r^2)\,(t)(D)(G)/(\%\text{ methane})$$

where:

Q = methane flow rate
R = radius of influence
r = borehole radius
t = waste thickness
D = density of waste
G = methane production rate.

As a rough approximation, the total flow from all wells as determined by the cylinder method, must be greater than or equal to Q_{tot} (Calculated above).

$$\Sigma\, Q \text{ from each well} \geq Q_{tot}$$

3.11.1.1.3. *Determine pressure drop required at each well to maintain assumed radius of influence.* The following equation is used to estimate the vacuum required to prevent the build-up of pressure within the landfill due to the generation of landfill gas:

$$\Delta P = \mu G_{tot} D \left[R^2 \ln(R/r) + (r^2/2) - (R^2/2)\right] / \, 2\, K_s$$

where:

ΔP = pressure difference from the radius of influence to the gas vent
R = radius of influence
r = radius of borehole
μ = absolute viscosity of the landfill gas
K_s = apparent permeability of the refuse
D = density of the refuse
G_{tot} = Total landfill gas production rate = G/(% methane)

In order to ensure that landfill gases generated within the landfill do not escape through the subsurface or through the cover, the vacuum used during full-scale operations will often be somewhat greater than the value calculated above. The required vacuum is often based on data collected from gas monitoring probes located at the perimeter of the landfill. These perimeter wells are typically monitored for vacuum and methane content.

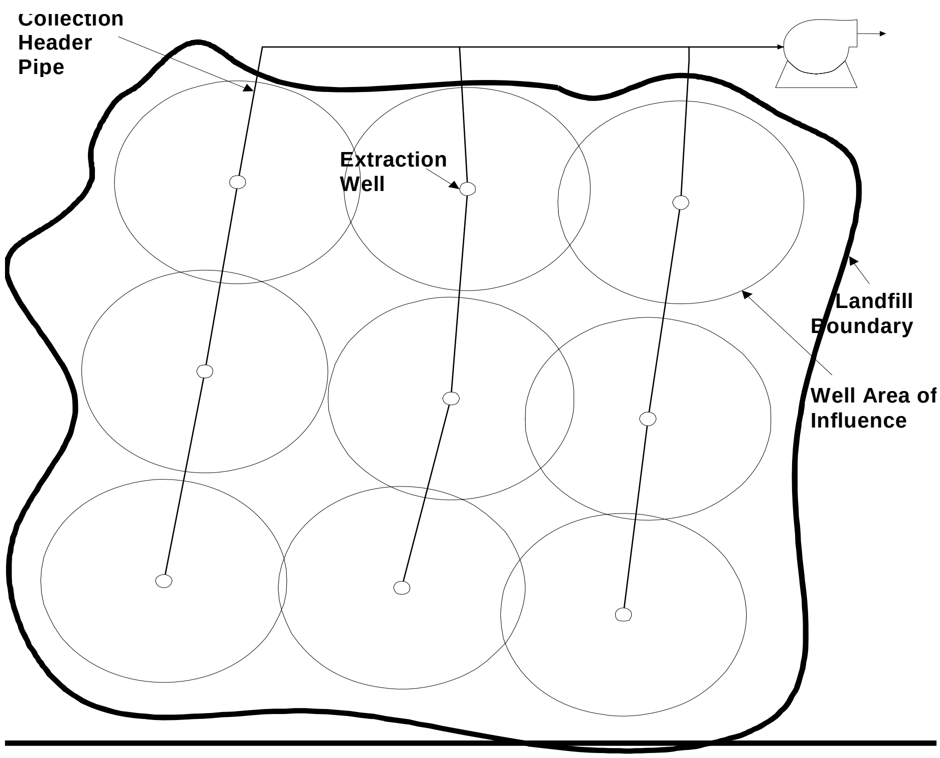

Figure 3.11. Typical Extraction Well Layout.

3.11.1.2. *Landfill Gas Generation Rate.* The equation shown in the previous paragraph requires the input of a gas generation rate. Methods to estimate the rate of methane generation were discussed in Chapter 2 of this EM. Estimates of methane gas generation rates have also been reported by numerous authors. Table 3.1 is a summary of reported values. It should be noted that the values reported in the table are representative of MSW landfills during their most active periods of gas production. Gas generation rates will decline as the waste ages. It should also be noted that methane is only one component of the gas being generated by a landfill. To conservatively estimate total gas production the values shown in Table 3.1 should be doubled.

Table 3.1.
Landfill Gas Generation

Methane Gas Generation Rate $m^3/(kg*day)$	**Reference**
3.29 to 20.1 × 10^{-6}	Bagchi, Amalendu, (1990). "Design, Construction, and Monitoring of Sanitary Landfills," John Wiley, New York
3.52 to 21.1 × 10^{-6}	Stecker, Phillip, (1989). "Active Landfill Gas Recovery Systems," University of Wisconsin Sanitary Landfill Leachate and Gas Management Seminar, Madison, WI, December 4-7.
3.56 to 20.5 × 10^{-6}	Emcon Associates (1980). "Methane Generation and Recovery from Landfills," Ann Arbor Science, Ann Arbor, Michigan
1.76 to 5.28 × 10^{-6}	Farquhar, Grahame J., (1989). "Factors Influencing Landfill Gas Recovery," University of Wisconsin Sanitary Landfill Leachate and Gas Management Seminar, Madison, WI, December 4-7.
1.76 to 7.04 × 10^{-6}	Ham, Robert K., (1989). "Landfill Gas Generation: Compositions, Quantities, Field Test Procedures and Uncertainty," University of Wisconsin Sanitary Landfill Leachate and Gas Management Seminar, Madison, WI, December 4-7.
27.4 to 54.8 × 10^{-6}	Ham, Robert K., Barlaz, Morton A., (1987). "Measurement and Prediction of Landfill Gas Quality and Quantity," ISWA International Symposium, "Process, Technology and Environmental Impact of Sanitary Landfills," Cagliari, Sardinia, Italy, October 20-23.
13.7 to 21.9 × 10^{-6}	Pohland, Frederick G., Harper, Stephen R. (1986), "Critical Review and Summary of Leachate and Gas Production from Landfills," EPA/600/2-86/073. USEPA, Cincinnati, OH.

3.11.2. *Other Design Considerations.* The maximum gas extraction rate from any well is limited by the available vacuum and air intrusion into the waste (i.e., overpull). Overpull can result in oxygen being pulled into the landfill and killing the methane producing bacteria or causing landfill fires. Additional items to keep in mind when establishing spacing of LFG wells:

- Shallower LFG wells have a smaller zone of influence.
- Extraction systems, whose primary purpose is migration control, should have a closer well spacing near the perimeter to minimize the potential for off-site migration.
- Access to proposed well locations by drill rigs must be considered when laying out the gas collection system.
- Disposal of drill rig waste.